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Lubrication

A Technical Publication Devoted to the Selection and Use of Lubricants

This Issue

NUCLEAR POWER PLANTS

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LUBRICATION

A TECHNICAL PUBLICATION DEVOTED TO THE SELECTION AND USE OF LUBRICANTS

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Vol. XLV September, 1959 No. 9

NUCLEAR POWER PLANTS

WHAT happened at Hiroshima changed the world's conception of the atom from something very small to a symbol of destructive power. This issue deals with the origin, peaceful development and beneficial application of Nuclear Power, and with the many unusual problems including lubrication that are being solved. As an aid to full appreciation of these problems, the following concise review of atomic structure is advisable.

ENERGY-MASS RELATIONSHIP

In 1905 Albert Einstein, the brilliant physicist and mathematician, conceived his theory that *energy and mass were equivalent* and wrote the deceptively simple equation

$$E = MC^2$$

which states that energy (E) is equal to mass (M) multiplied by the square of the velocity of light (C^2). Since light travels 186,000 miles in a second, C^2 is the very big number of 34,596,000,000—almost thirty-five billion. In other words Einstein's equation predicted that the atoms of even a small mass of matter contain a fantastic amount of energy: for example, one ounce of mass converted entirely into heat could change more than a million tons of water into steam.

In 1939 — thirty-four years later — Einstein's theory was proven by several scientists who discovered that the natural *fissioning* or splitting of "the" uranium atom (later identified specifically as uranium-235) converted some of its mass into energy.

ATOMIC STRUCTURE

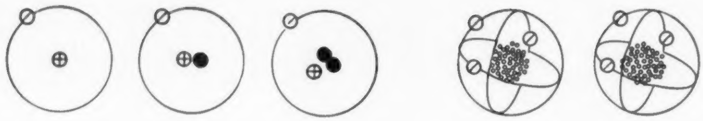
Recent measurements made with several different "atom smashing" equipments coupled with rather abstruse mathematics have enabled scientists not only to break apart and study the critical interior structure or *nuclei* of atoms but to artificially create new "man made" elements not previously identified in nature. These studies confirm that all *stable* atoms are composed of just three primary "building blocks" — protons, neutrons, and electrons.

Protons and Neutrons

Various combinations of *protons* and *neutrons* form any atom's nucleus: though of similar size and extremely dense mass, the proton carries a positive (+) electrical charge while the neutron is electrically neutral. The *mass number* of an atom is the sum of its protons and neutrons.

Electrons

An *electron* is a particle about 1/1800th the size of a proton and carries an equal but negative (−) electrical charge: it is so tiny that more than 2½ trillion electrons laid end to end would occupy only one inch. An atom's exterior "shells" contain from one to as many as 102 electrons. In a stable inactive atom, each negative electron is electrically counterbalanced by a positive proton. The number of protons (or electrons) present in the atom is its *atomic number* which designates the elemental family to which the atom belongs and which is sometimes used instead of a written name. As examples, hydrogen is element #1 while uranium is element #92.



MASS NUMBER (PROTONS + NEUTRONS)	1	2	3	235	238
ATOMIC OR ELEMENT NUMBER (PROTON - ELECTRON PAIRS)	1	1	1	92	92
ELEMENT	HYDROGEN	HYDROGEN	HYDROGEN	URANIUM	URANIUM
ISOTOPE NAMES	HYDROGEN-1 OR PROTONIUM	HYDROGEN-2 OR DEUTERIUM	HYDROGEN-3 OR TRITIUM	URANIUM-235	URANIUM-238
% NATURAL OCCURRENCE IN ELEMENT	99.98	0.02	0.0000000001	0.7	99.3
STABILITY	STABLE	STABLE	RADIOACTIVE	RADIOACTIVE	RADIOACTIVE
NUMBER OF PROTONS ⊕	1	1	1	92	92
NUMBER OF NEUTRONS ●	0	1	2	143	146
NUMBER OF ELECTRONS ⊘	1	1	1	92	92
NUMBER OF ELECTRON "SHELLS"	1	1	1	7	7

Figure 1 — Atomic structure of the hydrogen and two uranium isotopes

Isotopes

Originally it was believed that all the individual atoms in any quantity of elemental material like hydrogen were exactly alike: now it is certain that all but a few of the currently known 102 elements (10 of these being man-made) contain several different *isotopes* or "varieties" of the basic element and something over 3000 isotopes have been identified. In other words, an element can no longer be regarded as a single individual but instead is a family group composed of individual isotopes.

The isotopes of a given elemental family all have exactly the same number of electrons in their external atomic shells; consequently, they behave exactly alike during the formation of chemical compounds and, therefore, cannot be separated from each other by purely chemical methods. However, the nucleus of each isotope in an elemental family has its own distinctive number of *neutrons* and this number is simply the difference between its *mass number* and *atomic number*.

The lightest and simplest of all atoms are those three isotopes of the hydrogen family which are schematically diagrammed in Figure 1. For emphasis, similar diagrams for uranium-235 and uranium-238 (which are at the opposite heavy end of the atomic scale) are also shown; however, the veritable clouds of electrons around these huge complex uranium atoms cannot be pictured accurately. All five of the isotopes shown in Figure 1 occur naturally but, as the percentage figures indicate, some are exceedingly scarce. Fortunately, however, tritium and many other extremely useful isotopes can now be made readily with the aid of nuclear reactors.

Radioactivity

In 1896 Antoine Becquerel of France accidentally discovered that a piece of the heavy black uranium ore called pitchblende had mysteriously darkened a nearby unexposed photographic plate, apparently by giving off an emanation or radiation which passed through the protective cover on the plate. In 1898 Pierre and Marie Curie of France isolated a salt of the new element *radium* from pitchblende, determined that it was the principal source of Becquerel's mysterious radiation, and found that neither heat nor pressure would alter its steady rate of emanation. Thus, radium was the first *naturally* radioactive element to be discovered and scientists correctly concluded that its emanations came from deep within its atoms. In fact, this radiation is a form of energy produced by a change in mass or stepwise "decay" of the radium atom into other lighter isotopes and eventually into common wholly-stable metallic lead. The life of a radioactive isotope may be as short as a few fleeting millionths of one second or as long as many millions of years. Since radiation is readily detected and measured by such instruments as the Geiger counter, radioactive isotopes (either natural but commonly artificial) used as "tracers" give scientists an invaluable new tool for applying radiation, for measuring mechanical changes, and for studying com-

plex chemical reactions in petroleum[A], medical and agricultural research.

Chemical Versus Nuclear Reactions

Ordinary *chemical* reactions such as oxidation and reduction involve only the electrons of an atom: its nucleus is undisturbed, and the atom is therefore perpetually reusable. For example, when the carbon atoms in coal react (burn) with oxygen atoms in the air, they join together to make molecules of carbon dioxide, a gaseous chemical compound, and give off useful heat.

$$C + O_2 \longrightarrow CO_2 + \text{heat}$$

Any green living plant is continually proving that this reaction is reversible and that the atoms in such a molecule are unchanged. Through a process called photosynthesis, the plant uses sunlight energy to take carbon dioxide molecules apart, reuses the carbon to build other molecules within itself and returns pure oxygen to the air.

On the other hand, anything which changes the nucleus of an atom also changes the entire nature of the atom, and the change is irreversible. Radioactivity, transmutation, fusion and fission all affect the nucleus and therefore change the original atom into something quite different.

Fissioning

As far back as 1914 the English physicist Ernest Rutherford had predicted: "It is possible that the nucleus of an atom may be altered by direct collision with very swift electrons or atoms of helium (alpha particles) such as are ejected from radioactive matter." Since that time a large number of different types of *accelerators* have been developed which can impart high velocities to a number of *electrically charged* particles (electrons, protons, deuterons, alpha particles, nuclei and positive ions of elements heavier than helium) and can use such projectiles to bombard and change the nuclei of many isotopes into others. These machines are inefficient in the power sense since they require the *application* of immense quantities of power to achieve a proportionally tiny reaction and are mostly impractical for anything but research. The resultant reactions also cease as soon as the external power is turned off, i.e., the reactions are not self-sustaining. These machines are handicapped by the fact that their electrically-charged projectiles are easily deflected by either the protons or electrons of the "target" atoms, consequently, a low proportion of hits are made. In 1932 Sir James Chadwick discovered the electrically-neutral *neutron* which became the nuclear physicist's most effective projectile.

Lettered references are to page footnotes; *numbered* references pertain to the extensive bibliography at the end of this issue.

[A] Magazine Lubrication Dec. 1955, "Application of Radioactive Tracers in the Petroleum Industry."

By bombarding various materials with neutrons, many new isotopes of various elements can be made, and many of these isotopes can be made radioactive. Certain atoms when they absorb neutrons may split into two or more parts with the simultaneous emission of additional neutrons, thus giving rise to a chain "fission" reaction. The only atoms which can sustain such a chain fission reaction are uranium-235, plutonium-239 and uranium-233. Of these three, only uranium-235 is found in nature (0.7% in bulk uranium), however plutonium-239 and uranium-233 can be man-made in atomic piles from the fairly plentiful uranium-238 and thorium-232 respectively by causing each to absorb an additional neutron. As indicated by their mass numbers, these progeny are heavier than their parents and the process is termed a *breeder reaction*. The principal function of Oak Ridge was to separate and concentrate uranium-235 from bulk uranium.

If more than a minimum quantity (called the *critical mass*) of uranium-235 is merely brought together compactly, the mass immediately becomes "critical" and accelerated fission occurs, as diagrammed in Figure 2. Unless controls are provided, this reaction results in an atomic bomb detonation with its practically instantaneous evolution of huge quantities of heat and radiation. For the peaceful production of power, however, the same reaction is slowed down and controlled by means of *control materials* to give the desired steady controllable production of heat that is readily converted into

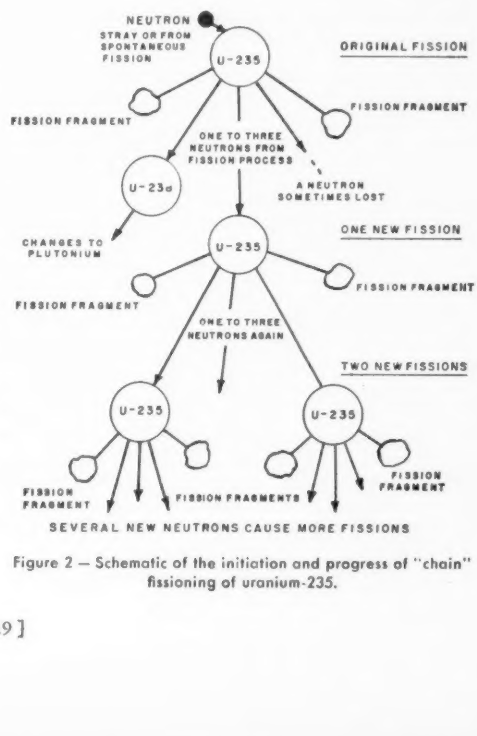
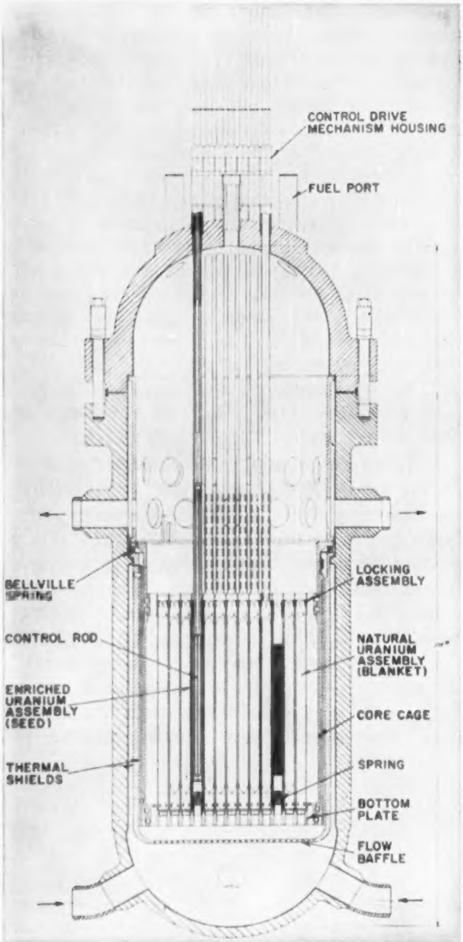


Figure 2 — Schematic of the initiation and progress of "chain" fissioning of uranium-235.



Courtesy of Westinghouse Electric Company

Figure 3 — Core and pressure vessel of the Shippingport heterogeneous pressurized-water nuclear reactor. Height, 33 feet; inside diameter, 9 feet; wall thickness, almost 9 inches including ¼ inch stainless steel lining; weight including uranium, more than 250 tons.

industrial power. Control is achieved most simply by inserting rods containing cadmium or boron into the critical mass, since these two elements absorb surplus neutrons. Neutrons ejected from any fissioning material are of the "fast" type which are not as effective in producing further fissioning as the "slow" or "thermal" type. *Moderator materials* such as water, graphite and paraffin wax which have the property of slowing down fast neutrons to thermal neutrons without appreciably absorbing them are, therefore, inserted into the reactor.

The first "pile", using graphite and uranium with cadmium-coated steel control rods was built in Chicago by Enrico Fermi and first sustained a controlled chain reaction on December 2, 1942.

Expanded versions of this same natural uranium-graphite reactor are being used to generate power and produce plutonium-239. The use of *enriched uranium* (a mixture of U-238 and U-235 in which the proportion of the latter highly-fissionable material has been artificially increased) permits a reduction of pile size while maintaining power output.

There are many other reactor types which are under investigation, several of which are built in pilot model scale.

Fusion

Not satisfied with splitting the atom, scientists are now trying to achieve controlled atomic *fusion*. Life as we know it would not exist without atomic fusion, as this is the way that our sun produces sunlight: by a fusion reaction of hydrogen to helium at tremendously high temperatures. In this nuclear reaction, some mass is converted into energy. Hydrogen fusion has been achieved on earth in the Hydrogen Bomb which uses an A-Bomb as a detonator to furnish the triggering heat.

Unlike fission, there are no long-lived radioactive, poisonous isotopes formed in the *fusion* reaction. Heavy hydrogen (deuterium), the preferred H isotope for fusion, can be obtained in unlimited supplies from sea water. The main problem is to produce and control the fantastically high temperatures (100,000,000°K) needed for fusion, and to keep them from melting the reactor vessel. So far this has not been achieved.

Shielding

Not indicated in Figure 2 are several other products of the fission reaction such as emanations of alpha particles (helium nuclei), beta particles (electrons) and gamma type radiation which could affect surrounding personnel and materials. Alpha and beta particles and fission fragments have but little penetrating power and are easily guarded against. Gamma radiation however has shorter wavelength and correspondingly higher penetration than X-rays: *shielding* of steel, metallic lead, massive sections of concrete and other materials is accordingly required to confine both gamma radiation and neutrons.

The shielding and safety aspects of present nuclear power reactors have been so well worked out that personnel are well protected, and conventional lubricants are satisfactory for the turbine and most auxiliary equipment bearings *which are outside the shield*. In most water-cooled reactors, water-circulating pumps and hydraulic control-rod actuators, which do get exposed to some radiation, are lubricated with water, which becomes only slightly and temporarily radioactive. Spent fuel elements are

removed and handled under water which serves as a radiation shield. The reprocessing of spent fuel is a costly and complex chemical operation, and is one reason why nuclear plants are uneconomic *at present.*

NUCLEAR POWER PLANTS

There are two general types of reactors, *homogeneous* and *heterogeneous*, and there are several sub types.

In *homogeneous* reactors, the fissionable material is dissolved or dispersed in a pumpable solution or slurry. This system has the advantage that fresh fuel can be pumped in easily while part of the old fluid charge can be drained off for reprocessing to remove accumulating waste products, which would otherwise absorb neutrons and thus "poison" the reaction. However, no large homogeneous reactors are operating because severe internal corrosion and other problems have not been overcome.

All the reactors to be described in the following are of the *heterogeneous* type in which the uranium or uranium compound is in shaped form, and usually enclosed or "clad" in corrosion and heat-resistant metal tubes which are supported in a metal frame work with intervening control rods. Figure 3 illustrates such an assembly (called a "core") together with its containing vessel.

The motion of the fission fragments is responsible for about 83% of the total energy liberated in a fission reaction and this energy is quickly converted into sensible heat by the impact of these fragments on adjoining atoms. This heat must be removed both to prevent damage to the core and to permit its conversion into useful power.

Purified water is used as the moderator, coolant and heat transfer agent in leading United States designs of heterogeneous reactors. A Boiling Water Reactor (BWR) allows the water to boil directly into pressurized steam[2]. However, in the Pressurized Water Reactor (PWR) diagrammed in Figure 4, sufficient pressure is maintained to keep the reactor water in fluid state and it is then circulated through heat exchangers which convert a secondary and separate supply of water into steam. When metallic uranium is used, reactor temperature must be kept low with the result that the steam produced has a temperature and pressure of only about 500°F and 600 psi. This temperature is quite modest when compared to the 1000°F or hotter steam being used in conventional oil or coal-fired power plants, and larger and more expensive steam turbines are therefore required to utilize it. Figure 5 presents a schematic comparison between conventional and nuclear steam power plants.

A recent advance on the temperature problem is

Courtesy of Westinghouse Electric Company

Figure 4 — Schematic of heat exchanger system used with one pressurized water reactor.

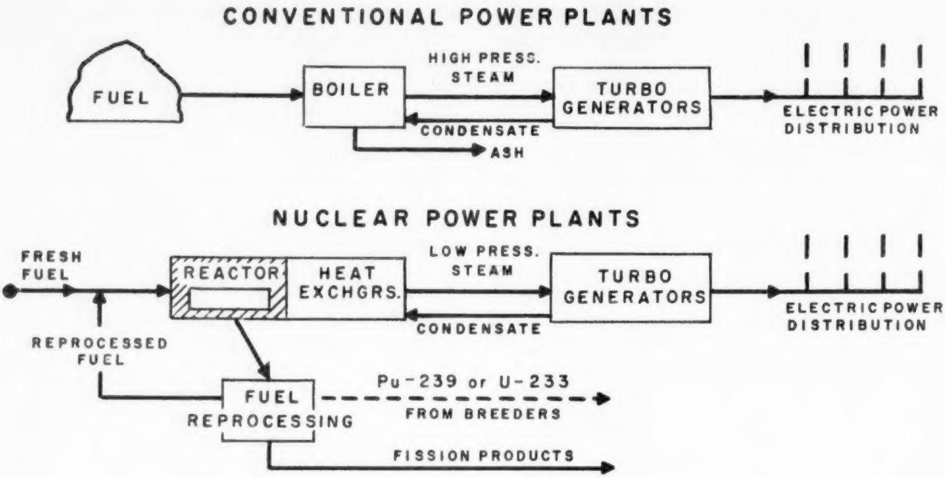


Figure 5 — Schematic comparison between conventional and nuclear steam power plants.

a reactor core composed of uranium dioxide pellets (in zircaloy jackets) which withstand higher operating temperatures than metallic uranium.

Most nuclear reactors are designed to have a *negative temperature coefficient of reactivity,* that is, as the reactor temperature tends to rise, the coolant becomes less dense and does not moderate or slow down the neutrons as efficiently, thus causing a slowing down of the nuclear fission. Therefore, control-rod action is mainly necessary only for start-up, shutdown, or during large changes in power level.

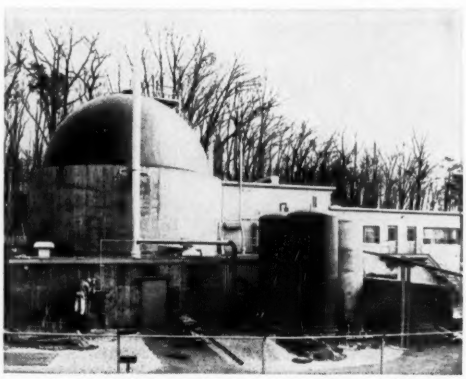
As exemplified by England's Calder Hall reactors, an inert gas such as carbon dioxide may also be use as a coolant and heat-transfer agent. These large piles use natural uranium rods set in a graphite lattice moderator. Since the uranium fuel is not enriched, these piles must be of substantial size to obtain enough neutrons. By 1965 England expects to supply 20 to 25% of its annual electric power requirements with gas-cooled reactors.

The United States is implementing its Atoms for Peace program[3] by offering enriched uranium, "know-how", and components to the Euratom agency composed of France, Western Germany, Italy, Belgium, Netherlands and Luxembourg. The USA target is to build approximately six major power reactors of proven types developed in the USA which will furnish approximately 1 million kilowatts by 1963. The over-all Euratom target is 14 million kilowatts by 1965.

A recent paper at the Fifth World Petroleum Congress predicts that USA nuclear power will become competitive in high-cost fuel areas beginning about 1968. This may occur somewhat sooner in England because of its high population density, depleted coal resources and high oil imports.[4] A second paper given at the Congress points out that nuclear reactors may turn out to be most important as a source of process heat, particularly if core radiation and that from fission fragments can be used to produce useful changes in material being processed[5].

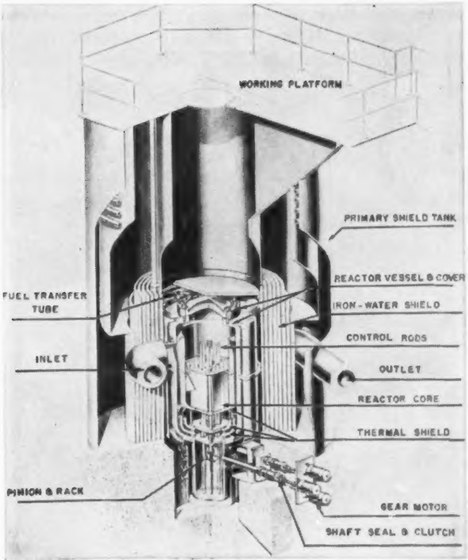
U. S. Army Packaged Power Reactor SM-1

Figure 6 pictures the exterior of the pilot model of this reactor which is located at Fort Belvoir, Virginia. Designed by Alco Products, Inc., it is one of the world's first nuclear plants built strictly for power generation. As indicated in Figure 7 it



Courtesy of U. S. Atomic Energy Comm.; Corps of Engineers, U. S. Army; Alco Products Inc.

Figure 6 — Exterior of first (pilot) model, U. S. Army, Packaged Power Reactor.



Courtesy of U. S. Atomic Energy Comm.; Corps of Engineers, U. S. Army; Alco Products Inc.

Figure 7 — Isometric drawing of reactor vessel, core and control rod structure in the U. S. Army Packaged Power Reactor. Two additional "safety" control rods which are normally in fully withdrawn position are not shown.

uses a pressurized-water reactor with fully enriched uranium fuel and has a generating capacity of 2,000 kilowatts. In operation since April, 1957 it has generated a total of 18,000,000 kilowatt-hours. Navy and Air Force operators are being trained, in addition to Army personnel, in this Defense Department project sponsored by the Atomic Energy Commission.

A second such plant, the SM-1A is now under construction near Fairbanks, Alaska. A third plant recently contracted for by the Army will be the first that is truly "packaged" and air-transportable, since all system components will be skid-mounted. Details of nearly a year's operation of SM-1 (formerly designated the APPR-1) have been described.[6]

Shippingport Plant

The first large-scale nuclear power plant in the United States went into operation in December, 1957 at Shippingport, Pennsylvania near Pittsburgh. Sponsored by the Atomic Energy Commission, this 60,000 kilowatt plant was designed by Westinghouse and uses the pressurized-water reactor shown in Figure 3. Operated by the Duquesne Light Company, the plant feeds its electrical output into the power system of that company. The reactor uses the so-called "seed-and-blanket" fuel concept which consists of seed cluster assemblies highly enriched in U-235 which give most of the initial power. The "blanket" part of the reactor is composed of natural uranium dioxide pellets, the U-238 portion of which is converted into plutonium-239 as the fissioning of the U-235 proceeds. The plutonium then fissions to give heat later in the life of the fuel charge.

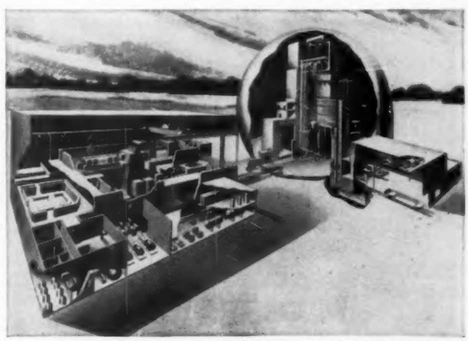
The Shippingport reactor generates steam at 600 psi through heat exchangers as diagrammed in Figure 4.

Dresden Power Plant

This plant, the first full-scale privately-financed nuclear plant to go into operation in the United States, and among the largest in the world, is being built by the Commonwealth Edison Company associated with the Nuclear Power Group Inc., (American Gas and Electric, Central Illinois Light, Illinois Power, Kansas City Power and Light, Pacific Gas and Electric, Union Electric Company of Missouri, and the Bechtel Corporation).

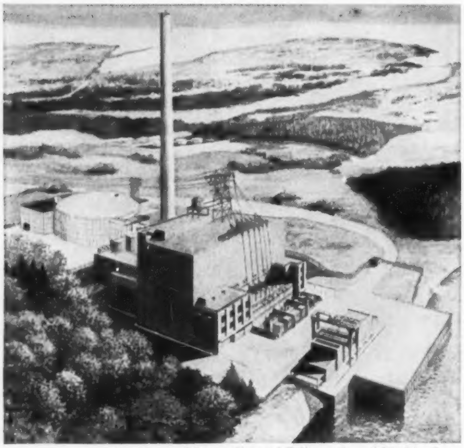
This plant is rapidly nearing completion at Dresden, Illinois near Chicago and will have a capacity of 180,000 kilowatts.[1] It is using a boiling water reactor designed by the General Electric Company and utilizes a slightly enriched uranium dioxide pellet core. The steam-water mixture produced in the reactor core flows to a primary steam drum where water and steam are separated. The steam flows to the turbine while the heated water is forced through the primary coils of a secondary steam generation system and then back to the reactor vessel. Primary steam is produced at 1000 psi and the secondary steam at 500 psi.

Figure 8 is a cutaway view of the sphere which contains the reactor and also shows the turbine and fuel-handling section.



Courtesy of General Electric Co.

Figure 8—Reactor sphere, reactor fuel-handling section, turbo-generator and associated equipment of Dresden boiling-water nuclear reactor.



Courtesy of Consolidated Edison Co. of N. Y., Inc.

Figure 9 — Indian Point pressurized-water breeder-reactor nuclear power plant.

It is expected that testing will start this fall and the plant will be in regular operation in the summer of 1960.

Indian Point Plant

The Consolidated Edison Company of New York is building a 275,000 kilowatt plant at its own expense on the east bank of the Hudson at Indian Point,[8] New York a few miles south of Peekskill. Figure 9 presents an artist's concept of the completed plant. This plant is a pressurized water type designed by Babcock and Wilcox and has two novel features.

The reactor will be thorium converter in which a blanket of thorium-232 will surround the highly enriched uranium core. As the reaction proceeds, uranium-233 will be produced from the thorium and will in turn fission to produce heat in the later stages of the life of the fuel charge.

The plant will use a superheater heated by fuel oil to raise the steam temperature to 1000°F and thus make a more efficient plant.

Construction of this very large plant is well along and again indicates the financial commitment which American industry is making in nuclear plants with an eye towards the future.

Enrico Fermi Fast Breeder Reactor

The Fermi Reactor[9] illustrated in Figure 10 and under construction on the shore of Lake Erie near Monroe, Michigan, will use molten sodium as a coolant and heat transfer medium and enriched uranium alloy rods as fuel. The reactor is called "fast" because the neutrons are not slowed down as much as in the "thermal" reactors. The elements of the breeder blanket surrounding the core will be made of depleted uranium rods recovered from a previous core charge. It is believed that this reactor will produce more new fuel (in the form of plutonium-239) than it consumes.

Molten metal coolants, such as sodium, have significant advantages such as excellent heat-transfer properties, and ability to operate at high temperatures without the necessity for pressurizing the reactor (because of the high boiling point of sodium). Drawbacks are the violent reaction of sodium with any moisture, and the formation of highly radioactive sodium-24 by neutron capture. This latter factor will require considerable shielding of the heat exchanger equipment used to transfer heat from the sodium to water and steam.

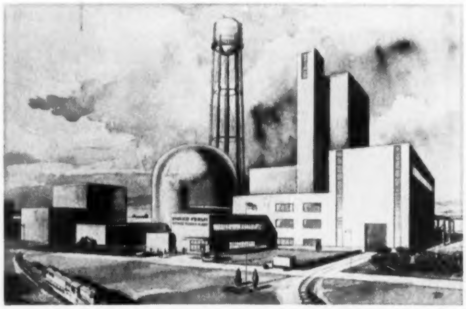
The Enrico Fermi station will generate 100,000 kilowatts with steam at 740°F and 600 psi. Designed by Atomic Power Development Associates Incorporated, it is being constructed under the AEC Power Reactor Demonstration Program but predominately financed by the Power Reactor Development Company, a non-profit organization of 23 companies. Power will be supplied to the Detroit Edison Company's distribution grid. The plant is scheduled to "go critical" in late 1960.

U. S. Submarine Nautilus

The most spectacular application of a nuclear reactor so far is considered to be that in the U. S. Navy Submarine Nautilus[10] illustrated in Figures 11 and 12 and subsequent submarines of this type.

The Nautilus was commissioned on September 30, 1954 and cast off on her maiden voyage on January 17, 1955. This epoch-making voyage opened up a completely new field of naval operations by demonstrating that a nuclear submarine could travel completely submerged for long periods of time. In fact the Nautilus cruised for two years on its first nuclear fuel charge, and covered 62,560 miles of which 34,498 miles were submerged.

Another record-breaking achievement was the

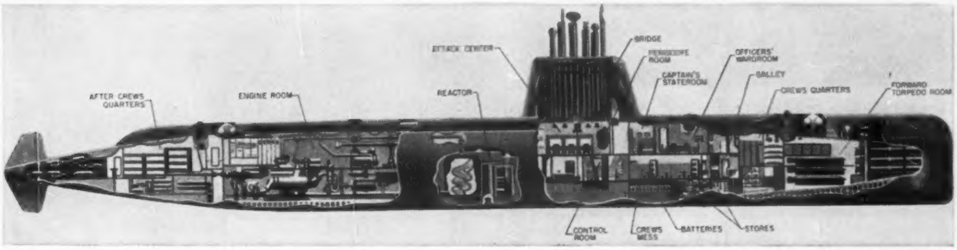


Courtesy of Atomic Power Development Associates, Inc.

Figure 10 — Enrico Fermi sodium-cooled fast breeder-reactor and power plant.

"Official United States Navy Photograph"

Figure 11 — U. S. Submarine Nautilus.



"Official United States Navy Photograph"

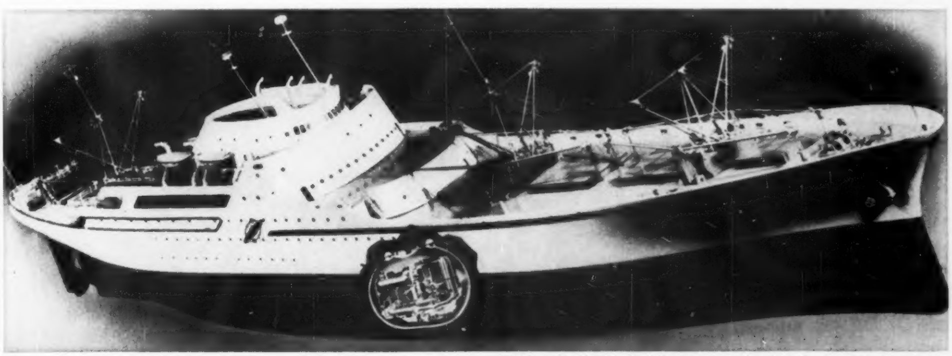
Figure 12 — Schematic of interior, U. S. Submarine Nautilus.

cruise of the Nautilus under polar ice in August 1958. This charted a new route from the Pacific to the Atlantic, travelling from Hawaii to Europe in 19 days. The Nautilus nosed under the Arctic ice near Port Barrow on the North Coast of Alaska on August 1: four days and 1830 miles later, this pioneering submarine surfaced near Greenland.

Details of the Nautilus reactor are not known except that it is a pressurized-water type using highly enriched uranium as the fuel. Five additional nuclear-powered United States submarines are now cruising. The U. S. Navy will have at least 30 "A-Subs" when those under construction are finished and contracts have been awarded for three more.

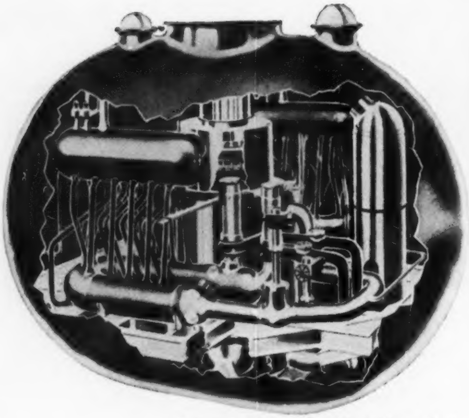
N.S. Savannah

The first nuclear-powered merchant ship is the N.S. Savannah,[11 12] now being built at Camden, New Jersey by the New York Shipbuilding Corpora-



Courtesy of New York Shipbuilding Corp., Merritt-Chapman & Scott Corp.

Figure 13 — Artist's drawing of the N. S. (Nuclear Ship) Savannah with insert showing approximate location of its pressurized-water type nuclear reactor.



Courtesy of New York Shipbuilding Corp., Merritt-Chapman & Scott Corp.

Figure 14 — Schema of the Savannah's reactor, heat exchange equipment and inclosure.

tion under joint sponsorship of the AEC and the U. S. Maritime Administration. Pictured in Figure 13 the Savannah is of the dry cargo type with accommodations for 60 passengers and a crew of 109 and will be operated by the States Marine Lines Inc. Its reactor, shown in Figure 14, was designed by Babcock and Wilcox and is of the heat-exchanger pressurized-water type to make 480 psi steam at 467°F. This 596-foot ship will cruise at 21 knots with its 20,000 shaft horsepower. The $30,000,000 vessel was launched July 21, 1959 and should be cruising under test in early 1960 with unrestricted operation expected by the summer. The N.S. Savannah will be used as a "floating laboratory" with a program of testing new designs of components.

A British authority[13] has predicted that the operating costs of nuclear-powered ships will be within

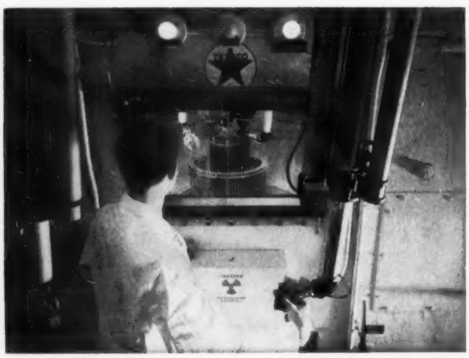


Figure 16 — View from outside of hot cell through 42-inch thick special safety window showing the large cobalt-60 source of gamma radiation in raised position. Operator is using one remote manipulator to adjust a stop cock.

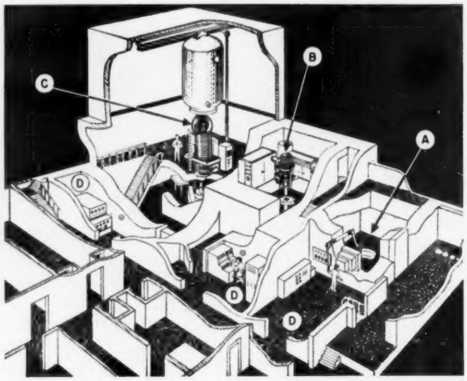


Figure 15 — Schematic drawing of radiation laboratory building showing locations of principal equipment and the massive shielding required.

five per cent of conventional ships by 1961. The fuel costs of the Savannah have been estimated by the same authority to be about twice those of oil at this time.

RADIATION STUDIES IN PETROLEUM RESEARCH

The extent of the investigation of the benefits to be derived from radiation by the petroleum industry is exemplified by the following descriptions:

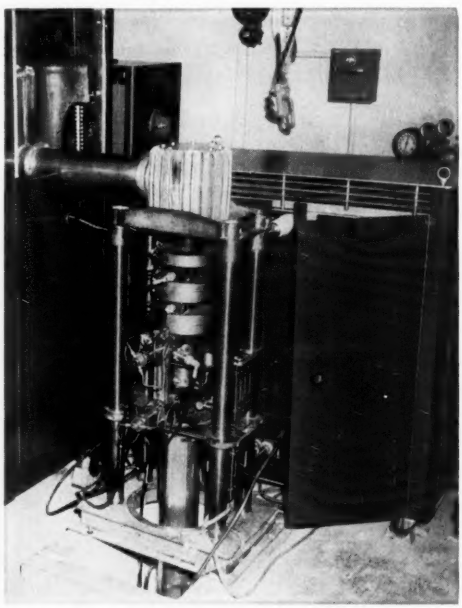


Figure 17 — Generating portion (in upper room) of electron linear accelerator.

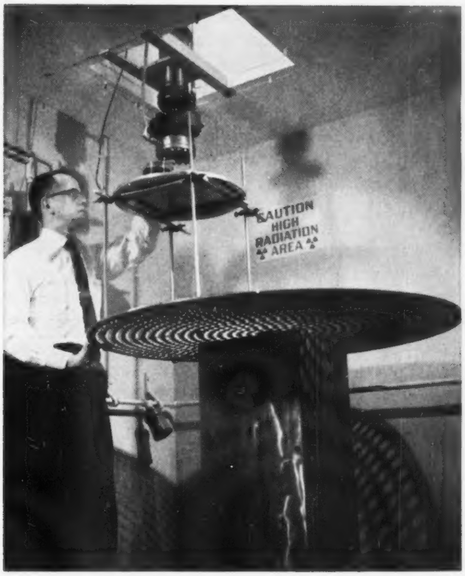


Figure 18 — Electron discharge tube and sample exposure table in lower room of electron linear accelerator.

In 1958, the largest amount in petroleum research of radioactive cobalt-60 was installed in the "hot cell" of a new million-dollar radiation laboratory designed and built especially by a prominent petroleum company to further expand its research with radioactivity.[14]

Schematic Figure 15 illustrates the unusual construction and heavy shielding of this laboratory, while the superimposed letters indicate its principal equipment as follows:

A. Cobalt-60 "Hot Cell"
B. Electron Linear Accelerator
C. Van de Graaff Proton Generator
D. Control Stations

Cobalt-60 "Hot Cell"

The gamma radiation emitted by the amount of cobalt-60 in this cell when installed was 29,100 curies, the equivalent of about 64 pounds of pure radium. Figure 16 taken from outside the heavily-shielded cell and through its 42 inch thick special window shows the ring of stainless steel "pencils" containing the cobalt-60 and surrounding a petroleum process apparatus. The arrangement and number of the cobalt-60 pencils can be varied to obtain desired intensities of gamma radiation, and other apparatus can also be adjusted by means of the two remote-control manipulators. The cobalt-60 rests on an elevator which is lowered into a deep well of water whenever anyone must enter the hot cell.

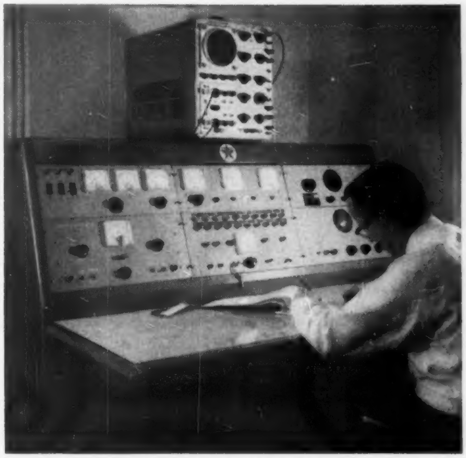


Figure 19 — Electron linear accelerator control panel.

Gamma radiation is so penetrating that it easily passes through the heavy steel vessels and heating jackets that are frequently employed in petroleum laboratory equipment. Thus the temperature, pressure and flow used in full scale refining processes can be duplicated in such laboratory equipment while subjecting the whole to gamma radiation.

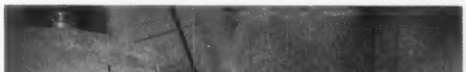


Figure 20 — Generating portion (in upper room) of Van de Graaff three million volt proton generator.

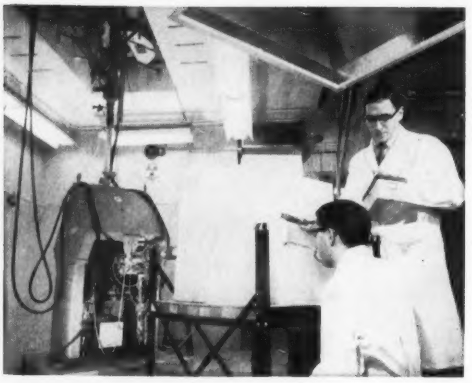


Figure 21 — Operators (in lower room) checking radioactivity of wax-inclosed sample after exposure to neutron beam from Van de Graaff generator.

Electron Linear Accelerator

Figure 17 shows the generating portion of the Electron Linear Accelerator power source and a Klystron tube located in the upper room which accelerate a concentrated beam of electrons (or beta radiation) to a speed more than nine-tenths the speed of light. Figure 18 illustrates placement of a laboratory sample under the electron discharge tube. The perforated motor-driven rotary table provides a convenient method for exposing many samples to the electron beam for precise intervals. Figure 19 shows the external control panel. This apparatus permits the concentration of a large amount of energy (in the high speed electrons) on a small sample. Since electrons have but little penetrating power, the sample must either be placed in a thin wall container or exposed directly. However, when electrons from this accelerator strike metals, highly penetrating X-rays are created, thus necessitating the heavy shielding around the instrument that is shown in Figure 15.

Van de Graaff Proton Generator

The right hand part of Figure 20 shows the upper or generating portion of the Van de Graaff generator with its heavy pressure tank temporarily removed and being placed at the reader's left. The instrument generates and uses three million volts to accelerate the protons or "positive ions" of hydrogen-2 (deuterium) nuclei and impinges them on a "target" of metallic beryllium which in turn releases neutrons. Figure 21 shows the tube containing the proton stream emerging from the ceiling into a large electromagnet which turns the stream horizontally and focuses it. The large block of material in the foreground is paraffin wax which surrounds the sample under study and acts as a moderator to convert the fast neutrons to the slow thermal type. Thus, the Van de Graaff is useful as an atom splitter to make minute quantities of radioactive isotopes and is the only one of the three instruments described which can modify atomic nuclei.

Other rooms included in the new radiation laboratory are a "hot lab" where radioactive materials can be handled, two organic chemical laboratories, a tracer lab and an analytical laboratory. The walls surrounding the radiation sources vary in thickness from 3½ to 7 feet.

By means of these new tools, the research scientists of this petroleum research organization are continuing their studies of the rearrangement of molecules in a way which is not possible with usual energy sources which (unlike radiation) cause severe heating as the material is being treated. Pertinent dosages of radiation energy can be used to bring about reactions which are not possible by any other means known today. For instance, it has been shown by a prominent electrical equipment manufacturer[15] that polyethylene can be made to resist melting by irradiation with electron beta rays and thereby increase its excellent electrical insulating properties. This radiation-modified plastic is now being used to insulate wires in electric motors which must run at high temperatures.

WHAT RADIATION DOES TO PETROLEUM PRODUCTS

Radiation changes petroleum (and also living plants and animals) in several ways, the amount and type of change depending upon the amount and type of radiation. Atoms become excited (made more reactive) by exposure to radiation and this effect leads to such chemical changes as breakage of chemical bonds and also the formation of free radicals.

The effects of radiation are generally *cumulative:* i.e. a short exposure to intensive radiation will produce the same effects as a longer exposure to weaker radiation of the same type. *Total* dosage rather than dosage rate is the most important.

A unit called the "*rad*"[B] is the most practical measure of radiant energy since it can be used regardless of the *type* or mixtures of type of energy that are involved. However, for gamma and X-ray type radiations only, the more common unit is the roentgen[C]. For gamma radiation one rad is roughly equivalent to 1.2 roentgens.

Alpha & Beta Particles

Near a nuclear reactor, petroleum products are not apt to be exposed to alpha and beta particles because of the low penetrating power of these forms of nuclear emissions. However, the high

[B] The absorption of 100 ergs of energy by one gram of material.
[C] Gamma or X-ray radiation required to impart 8.38 ergs of energy to one gram of dry air.

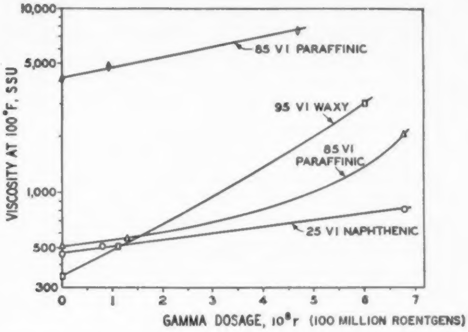


Figure 22 — Effect of gamma radiation on the viscosity of four straight-mineral oils (reprinted from 1957 article[16] titled, "Some Effects of Gamma Radiation on Commercial Lubricants" by J. G. Carroll and S. R. Calish, Jr.)

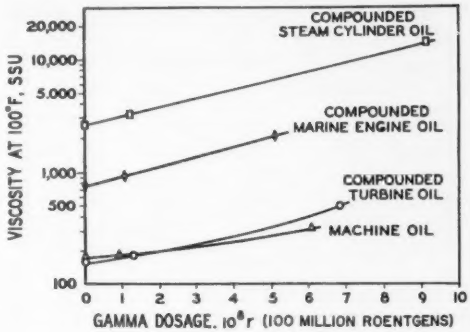


Figure 23 — Effect of gamma radiation on the viscosity of four compounded oils (reprinted from 1957 article[16] titled, "Some Effects of Gamma Radiation on Commercial Lubricants" by J. G. Carroll and S. R. Calish, Jr.)

energies of these particles would be extremely damaging to fuels and lubricants at short ranges because they ionize and dissociate the molecules causing changes in composition.

Gamma Radiation

Gamma rays are electromagnetic waves like X-rays, but of shorter wavelength and higher energy. Gamma rays originate in the nucleus of an unstable atom whereas X-rays come from the inner excited electron shell. On the other hand gamma rays of moderate intensity generally interact only with an atom's electron shells to cause ionization for example, but they do *not* affect its nucleus and therefore do *not* make it radioactive.

Fuels and lubricants become more reactive and change chemically with the absorption of gamma radiation: oxidation, evolution of gas and viscosity changes are accelerated. General levels of gamma radiation damage are as follows:

Total Dosage in Roentgens	*Effect*
200 to 800	lethal to humans
less than 5 million	generally negligible to oils and greases
5 million to 10 billion	organic fluids and greases are sensitive in this range
above 10 billion	Only the most resistant organic structures survive

Neutron Exposure

In addition to the changes brought about by other forms of radiation, neutrons can change organics in two other ways:
(1) fast neutrons collide with hydrogen nuclei, ejecting fast "recoil" protons which induce secondary ionization and (2) thermal neutrons are captured by the nuclei which then decay and emit charged particles and gamma radiation. The exposed material also becomes heated during these changes as the kinetic energy of the atoms is increased.

From a damage standpoint, one rad of neutrons causes 10 times more biological damage to living tissue than one rad of gamma radiation. For petroleum, the effects of these two radiation types are more nearly equivalent if some criterion such as viscosity increase is used as a measurement. On an energy deposit basis, neutrons may do more damage than gamma radiation, however it should be noted that such a comparison neglects the residual radioactivity that is induced by neutron radiation.

Effects of Radiation on Oils

It has been reported[16] that gamma radiation of 100 to 900 million roentgens caused mineral oils and additive oils with mineral oil base to darken and acquire an acrid, oxidized odor; however neu-

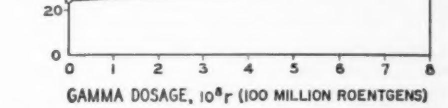


Figure 24—Effect of gamma radiation on the viscosity index of four straight-mineral oils (reprinted from 1957 article[16] titled, "Some Effects of Gamma Radiation on Commercial Lubricants" by J. G. Carroll and S. R. Calish, Jr.)

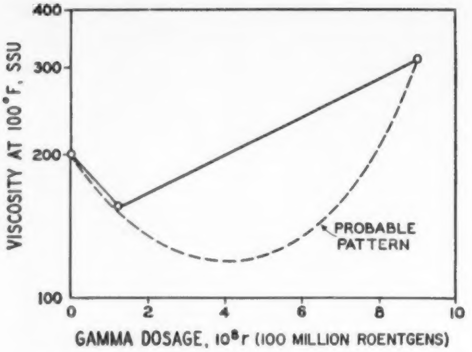


Figure 25 — Effect of gamma radiation on an automatic transmission fluid containing a viscosity index improver (reprinted from 1957 article[16] titled, "Some Effects of Gamma Radiation on Commercial Lubricants" by J. G. Carroll and S. R. Calish, Jr.)

tralization number increases were less than 0.5 and no sludge was evident. The evolution of gas in the form of hydrogen and light hydrocarbons also occurs and this may present a problem with sealed containers.

The curves of Figures 22, 23 and 24 indicate a general steady increase in viscosity and viscosity index with increasing gamma dosage. On the other hand Figure 25 indicates that an automatic transmission fluid which contains a viscosity index improver may behave quite differently. The initial decrease in viscosity was probably due to breakdown of the polymer-type viscosity index improver which effect was finally overbalanced by the thickening of the base oil.

Gamma radiation actually improved the anti wear characteristics of the above oils as measured by the Almen (bronze-steel specimens) and Falex (steel-steel specimens) tests. However, a MIL-L-2105 gear oil with its chlorine-containing additive also became very corrosive and gave off hydrochloric acid.

Effects of Radiation on Greases

Experimental work[17] has shown that greases generally first soften on irradiation because of disintegration of the soap structure then finally become porous and brittle due to polymerization and cross-linking of the oil molecules. Performance life in bearings is reduced and oxidation resistance is impaired. Low temperature torque is impaired only to a minor degree at about 500 million roentgens but increases for higher dosages, whereas copper corrosivity, evaporation and brass-steel gear wear are not greatly increased. Greases made from alkyl-aromatic fluids (benzene or naphthalene derivatives) and gelled with sodium terephthalamate or a treated silica are the most radiation resistant according to this study. Figure 26 shows the effect of gamma radiation on the life of ball bearings lubricated with a terephthalamate synthetic grease versus a conventional sodium soap mineral oil grease.

Recent papers in British journals[18-19] present valuable information on lubricants for use in gas-cooled graphite-moderated reactors. Radiation-resistant greases are commercially available, and these are replacing the previously used bonded solid films of molybdenum disulfide which were unsatisfactory as regards durability and moisture corrosion. Gas-blower oils of very low vapor pressure have been developed to avoid contamination of the gas.

Effects of Radiation on Petroleum Fuels

The military services are interested in the effect of nuclear radiations on supplies of petroleum fuels as well as on other petroleum stocks. A review[20] presented in 1957 gives rather comprehensive findings on a gasoline stock, kerosine, stove oil, JP-3, JP-4, and JP-5 jet fuels. Gamma radiation up to five billion roentgens, and also exposure to one billion billion neutrons/cm^2 from a nuclear pile were used. (An approximate relationship for damage from neutrons in this case versus damage from gammas, based on viscosity change only, is that 10^{18} slow neutrons/cm^2 correspond to damage inflicted by one billion 300 million roentgens.)

The following conclusions were made, basis this work.

1. The weight per cent of hydrogen decreases and density increases during irradiation.

2. Radiation above 100 million roentgens gamma dosage drastically changes the physical properties of fuels. Materials of both higher and lower molecular weight than the original are formed.

3. Gas is evolved during irradiation. The quantity may be as high as 20 volumes of gas per volume of fuel at 500 million roentgens and increases approximately linearly.

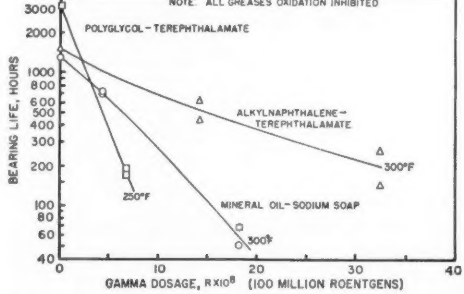


Figure 26 — Effect of gamma radiation on ball bearing life (reprinted from 1956 article[17] titled "Radiation Resistant Greases" by J. G. Carroll, R. O. Bolt and B. W. Hotten.

TABLE I
Radiation Effects on Lubricant Life in a Particular Nuclear Power Plant

Components	Operating Dosage Level, Rads/Hr.	Lubricant Life (Hours to attain 100 million Rads Exposure)
Turbine	0.2	1 billion
Water Circulating Pumps	100	1 million
Remote Fuel Handling Devices	100,000	1000
Control Drive Mechanisms	100,000	1000
At Reactor Vessel Wall	1 million	100
At Reactor Core Center	10,000 billion	$\frac{1}{100,000}$

4. Radiation causes viscosity increases, although this is not appreciable below about 500 million roentgens.
5. Olefin type hydrocarbons appeared to increase appreciably during irradiation, although present methods do not permit a quantitative assessment of this change.

LUBRICATION PROBLEMS IN NUCLEAR POWER PLANTS

Water-Cooled Reactors

As described earlier in this article, water-cooled and water moderated reactors dominate the American scene. Most of these plants use water for the lubrication of critical bearings, for example, graphoid bearings of "canned" pumps.

A leading electrical equipment company has thoroughly studied the lubrication aspects of a nuclear power reactor of the boiling water type, based on a 12,500 kilowatt plant.[2] The following conclusions, basis *adequate shielding*, stable turbine oils and suitable relubrication periods were made:

"The over-all lubrication problems in a nuclear power plant will be very similar to those encountered in conventional steam power generating stations. Thermal and oxidative degradation conditions will be similar for petroleum lubricants in the two types of stations. The same general types of oils and greases will be employed, the relubrication schedules and inspection periods will be similar in length, and only minor attention must be paid to the possibility of the build-up of radioactive contaminants in the oil. The problems will vary only slightly with the type of nuclear power plant system employed since there will be the same general types of equipment to be lubricated and the radiation shielding will be similarly arranged for ready maintenance of the equipment."

Table I gives the calculated dosage levels at various points in this 12,500 KW boiling-water power plant and shows how lubricant life is affected. As the turbine oil is exposed only to slight gamma radiation of about 0.24 roentgens (0.2 rads) per hour from the slightly radioactive steam, it does not itself become radioactive, and the used oil *in this case* could be handled in the same fashion as any other used turbine oil. It may be expected that radiation intensity decreases tremendously with distance from the reactor core. The radiation levels quoted in Table I are for a particular small plant and the reader is cautioned that larger plants or those of different design may well have quite different radiation levels at the various points in the system.

Oils containing metallic additives such as sodium, or metallic contamination, will become radioactive to a greater degree than straight mineral oils or those containing phosphorus and/or sulfur additives *if exposed to neutron bombardment.* Here again the question of whether such oils will become dangerously radioactive depends upon how close they are to the nuclear core where the fission reaction is taking place. The conventional 150 SUS viscosity turbine oil *used as an example* (such an oil would not be used inside the reactor shield) requires one billion hours to accumulate 120 million roentgens (100 million rads) of radiation dosage which is the approximate dosage level at which the oil begins to thicken excessively. This is because the turbine is so well shielded and so far removed from the "hot" core that the operating dosage level is very low for the design in question. Basis operating experience at the plants discussed earlier in this article, conventional lubricants are satisfactory for all points in water-moderated plants not lubricated by water.

Lubricants other than turbine oils will be those for the coolant circulation pumps, and for remote fuel handling and control rod mechanisms.

Gas-Cooled Reactors

A very recent article[18] describes the lubrication

requirements of United Kingdom plants of the graphite-moderated carbon-dioxide-cooled type. Applications where specially formulated products are needed include fuel charge and discharge machines, reactor servicing machine, and control rod mechanisms. Fuel elements must be changed during full operation at about 200°C (392°F) to 400°C (752°F), in the presence of neutrons and gamma rays, and of hot carbon dioxide under pressure of about 150 psi.

EFFECTS OF RADIATION ON HUMAN BEINGS

The maximum permissible dosage for workers is usually given as only *0.3 roentgens per week* for those over 18 years of age (younger persons should not be employed for nuclear radiation work because of genetic considerations). The maximum permissible *yearly* dose is 5 roentgens, which averages 0.1 roentgen for a 50-week work year.

Table I shows that the radiation intensity around the turbine of the 12,500 KW reactor is 0.2 rads per hour of gamma energy which is equivalent to 0.24 roentgens per hour. Therefore, a man working around the turbine while the nuclear fission reaction is occurring would receive his maximum *weekly* dose in approximately *one hour*. However, when the reactor is closed down (i.e. made "sub-critical") the radiation from the radioactive steam or condensed water in the turbine dies out rapidly. Therefore, after a wait of only a few moments, the overall radiation level is low enough so that it would not interfere with maintenance operations on the turbine itself. This estimate, of course, is based upon the particular type, size and power rating of the reactor described in Table I.

SUMMARY

The petroleum industry is interested in nuclear energy both as a heat source and as a source of radiation energy. It has been one of the pioneers in the use of radioactive isotope tracers. Lubrication problems are being solved as they arise.

The brainpower and financial support being allotted to studies of radiation chemistry and physics by leading petroleum companies make it evident that this new source of energy is being fully explored. New and improved products and processes may be expected to result from such intensive research.

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